



# SISTEMI NON CONVENZIONALI PER IL MONITORAGGIO DEI PONTI ESISTENTI: Dal Weigh-in-motion all'interferometria satellitare

02/09/2021

Filippo Ubertini, Ilaria Venanzi

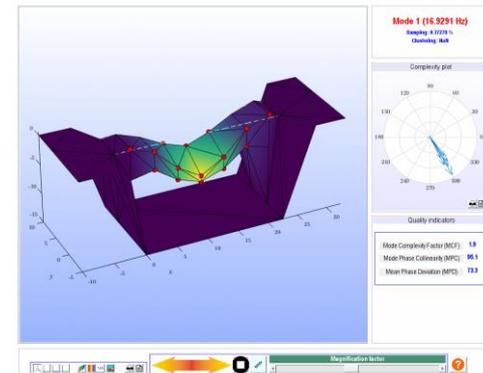
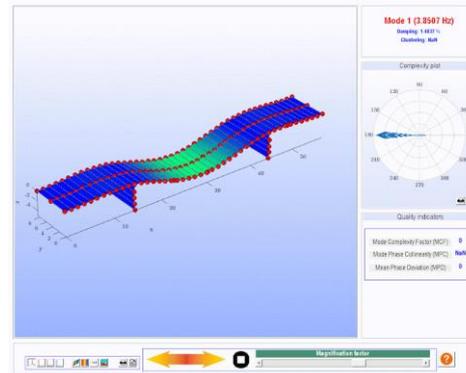
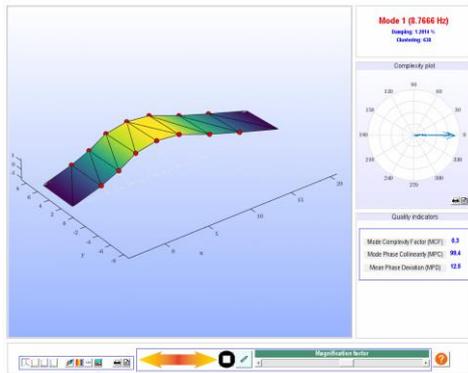
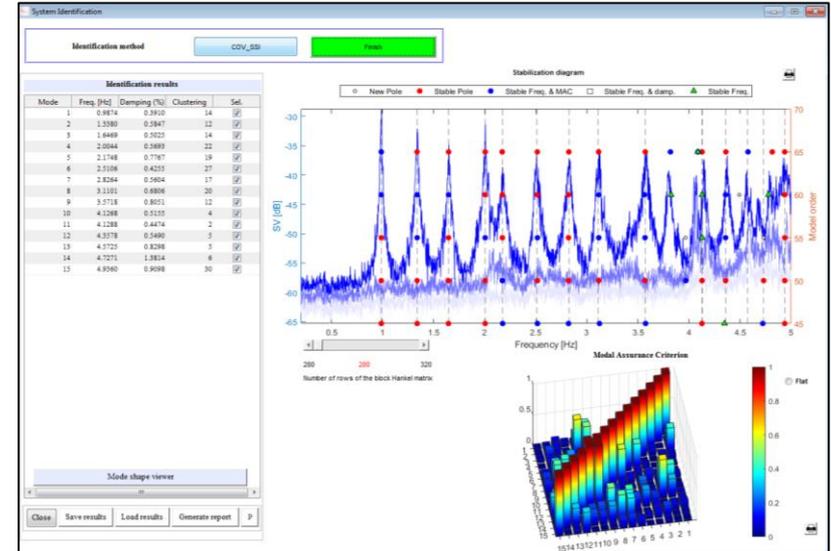
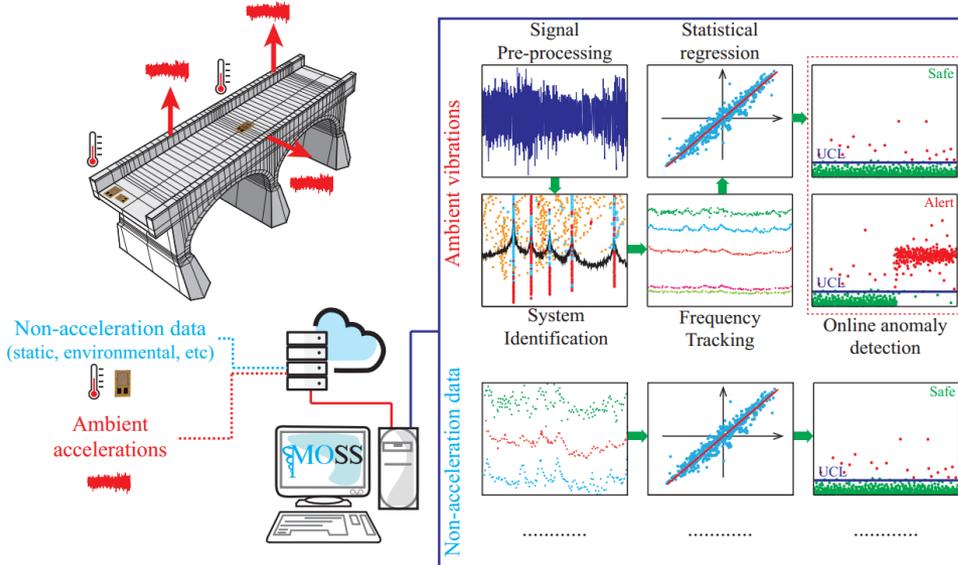
# OUTLINE

- Analisi **non convenzionale** di segnali di monitoraggio
  - OMA+AI
  - Interferometria sismica
- Sensoristica di monitoraggio **non convenzionale**
  - INSAR
    - Quantificazione degli errori
  - WIM
    - Pavimentazioni intelligenti
    - Analisi di costo

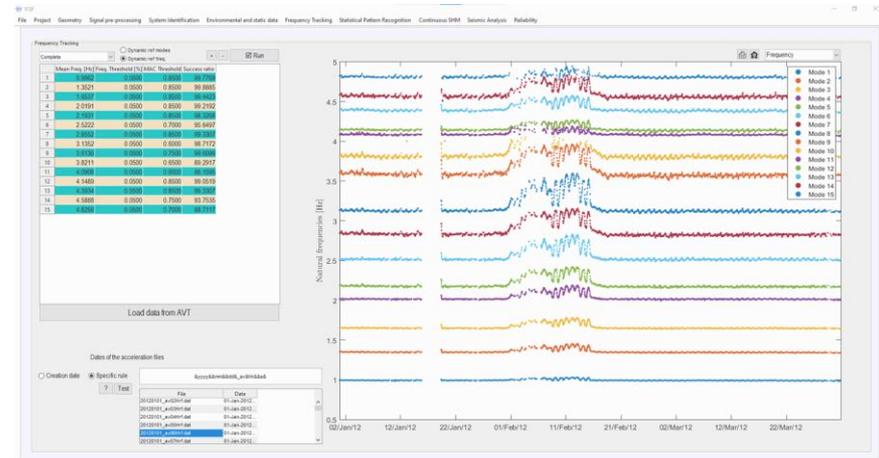
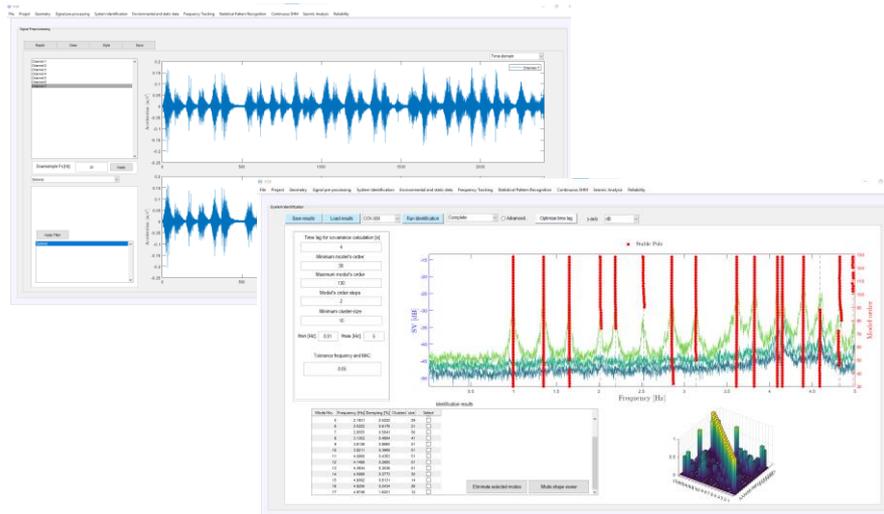
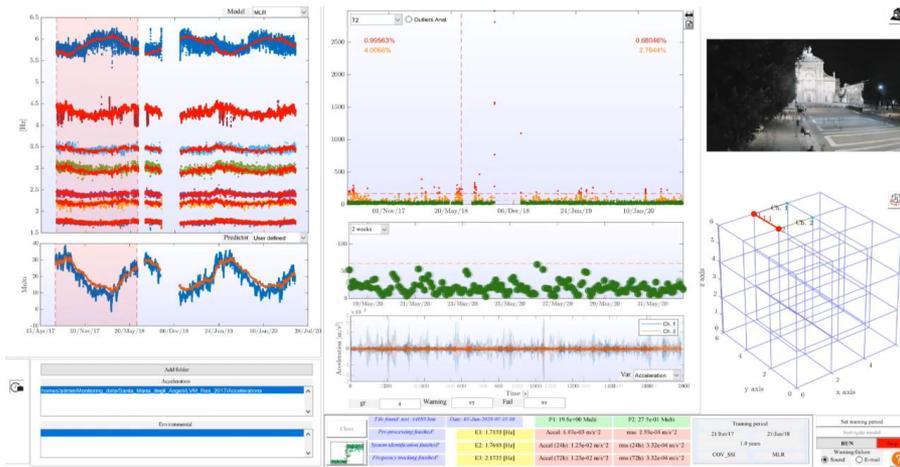
# ANALISI NON CONVENZIONALE DI SEGNALI DI MONITORAGGIO



MOVA/MOSS: Two integrated software solutions for comprehensive Structural Health Monitoring of structures  
 Enrique García-Macías and Filippo Ubertini.



# ANALISI NON CONVENZIONALE DI SEGNALI DI MONITORAGGIO



<https://www.youtube.com/watch?v=LerhtV8Zk4o>

# ANALISI NON CONVENZIONALE DI SEGNALI DI MONITORAGGIO

## Interferometria sismica

### Impulse response functions

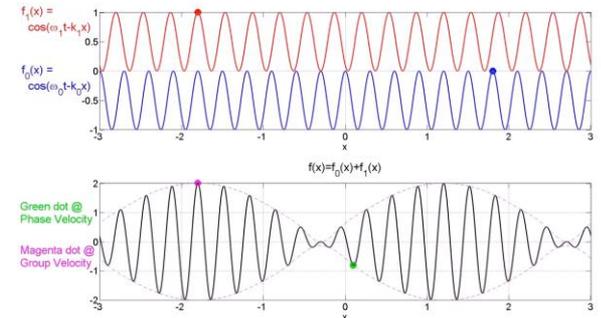
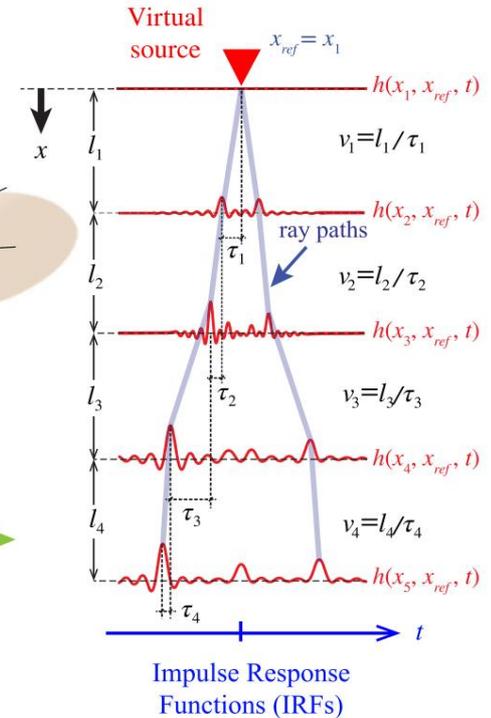
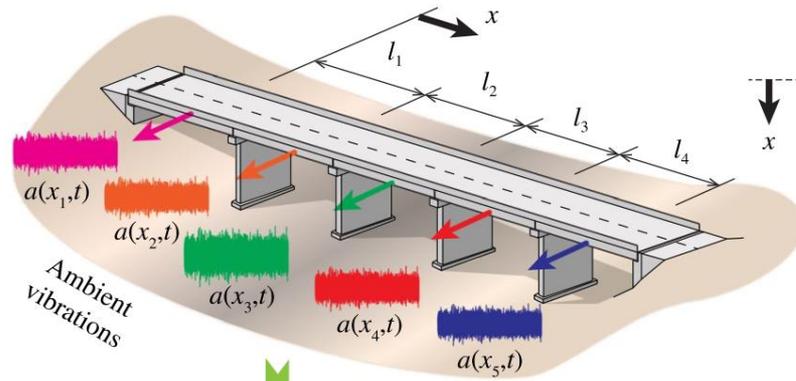
$$u(z, t) = u(z_{ref}, t) * h(z, z_{ref}, t) = \int_0^t u(z_{ref}, s) h(z, z_{ref}, t - s) ds$$

$$h(z, z_{ref}, t) = \mathcal{F}^{-1} \left\{ \widehat{h}(z, z_{ref}, \omega) \right\} = \mathcal{F}^{-1} \left\{ \frac{\widehat{u}(z, \omega)}{\widehat{u}(z_{ref}, \omega)} \right\}$$

**Transfer function**

**Green's function**

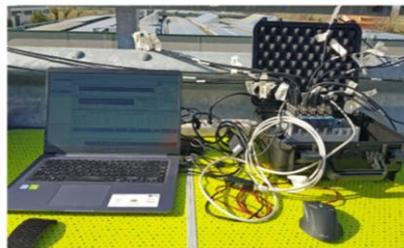
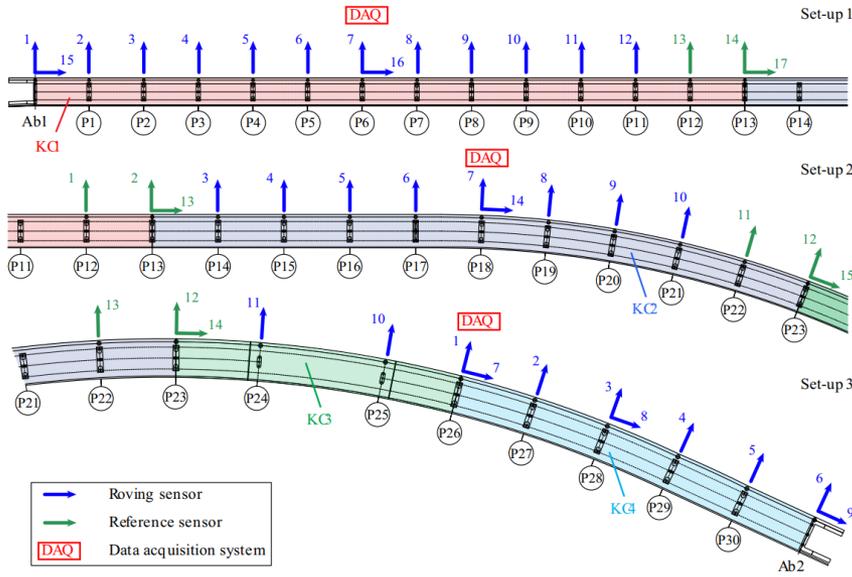
$$h(z, z_{ref}, t) \approx \mathcal{F}^{-1} \left\{ \frac{\widehat{u}(z, \omega) \overline{\widehat{u}(z_{ref}, \omega)}}{|\widehat{u}(z_{ref}, \omega)|^2 + \epsilon} \right\}$$



García-Macias, E., & Ubertini, F. (2021). Structural assessment of bridges through ambient noise deconvolution interferometry: application to the lateral dynamic behaviour of a RC multi-span viaduct. Archives of Civil and Mechanical Engineering, 21(3), 1-20.

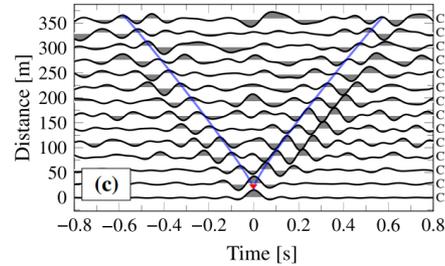
# ANALISI NON CONVENZIONALE DI SEGNALI DI MONITORAGGIO

## Interferometria sismica

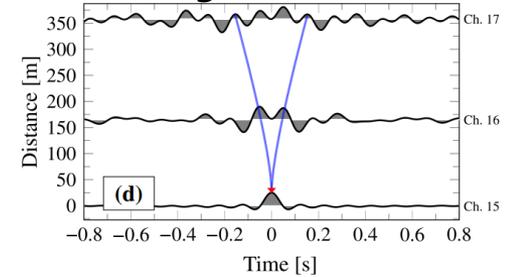


García-Macías, E., & Ubertini, F. (2021). Structural assessment of bridges through ambient noise deconvolution interferometry: application to the lateral dynamic behaviour of a RC multi-span viaduct. Archives of Civil and Mechanical Engineering, 21(3), 1-20.

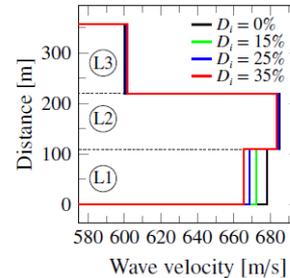
## Transverse waves



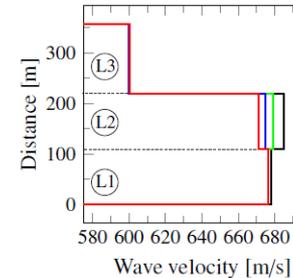
## Longitudinal waves



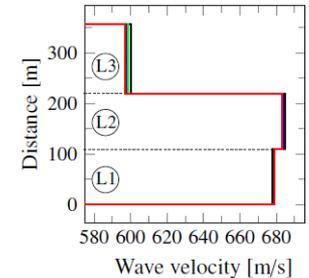
(a)



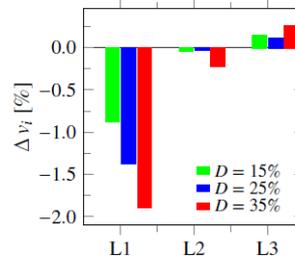
(b)



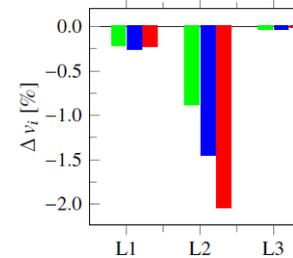
(c)



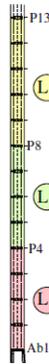
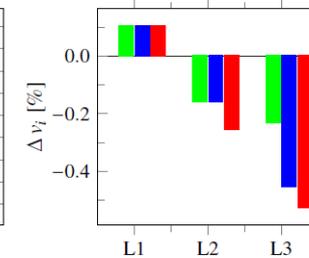
(d)



(e)



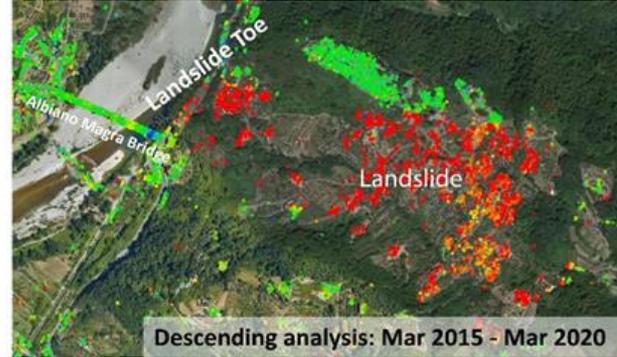
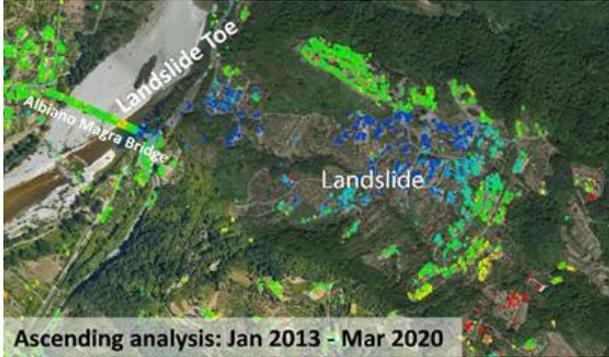
(f)



# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR



Ponte di Albiano Magra, prima e dopo il crollo avvenuto l'8 aprile 2020



Mean velocity (mm/year)

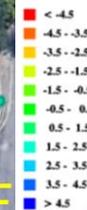


Rilevamento di un movimento franoso lungo il pendio a Est del ponte

e-geos  
AN ASI / TELESPAZIO COMPANY

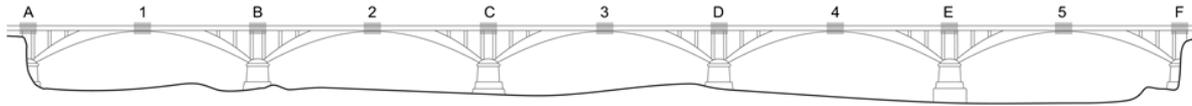


Mean velocity (mm/year)  
28/1/2013 - 05/4/2020

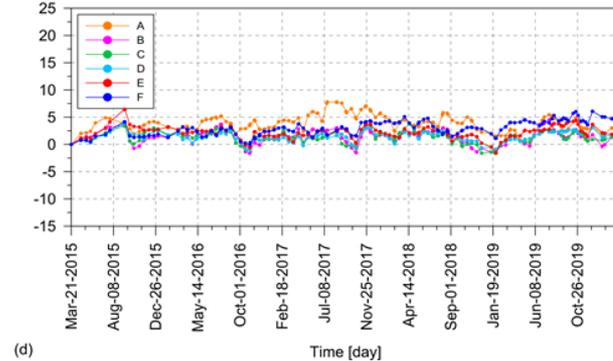
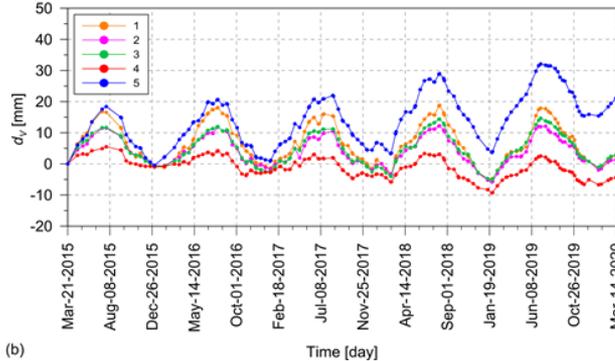
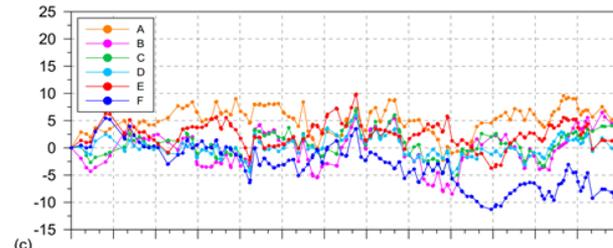
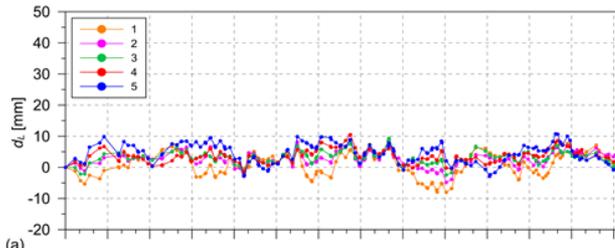


e-geos  
AN ASI / TELESPAZIO COMPANY

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR



COSMO-SkyMed  
 $\theta_A = 32.2^\circ$ ,  $\alpha_A = 168.6^\circ$   
 $\theta_D = 29.4^\circ$ ,  $\alpha_D = 10.3^\circ$



$$\hat{\mathbf{d}} = \mathbf{B}^{-1} \mathbf{d}_{\text{LOS}}$$

ASS#1. vettore  $\mathbf{d}$  nel piano  $L-V$

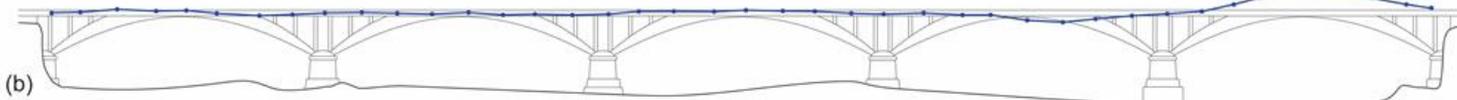
$$\hat{\mathbf{d}} = \begin{Bmatrix} \hat{d}_L \\ \hat{d}_V \end{Bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \sin \theta_A \cos(\alpha_A - \varphi) & \cos \theta_A \\ \sin \theta_D \cos(\alpha_D - \varphi) & \cos \theta_D \end{bmatrix}$$

25 Marzo 2016

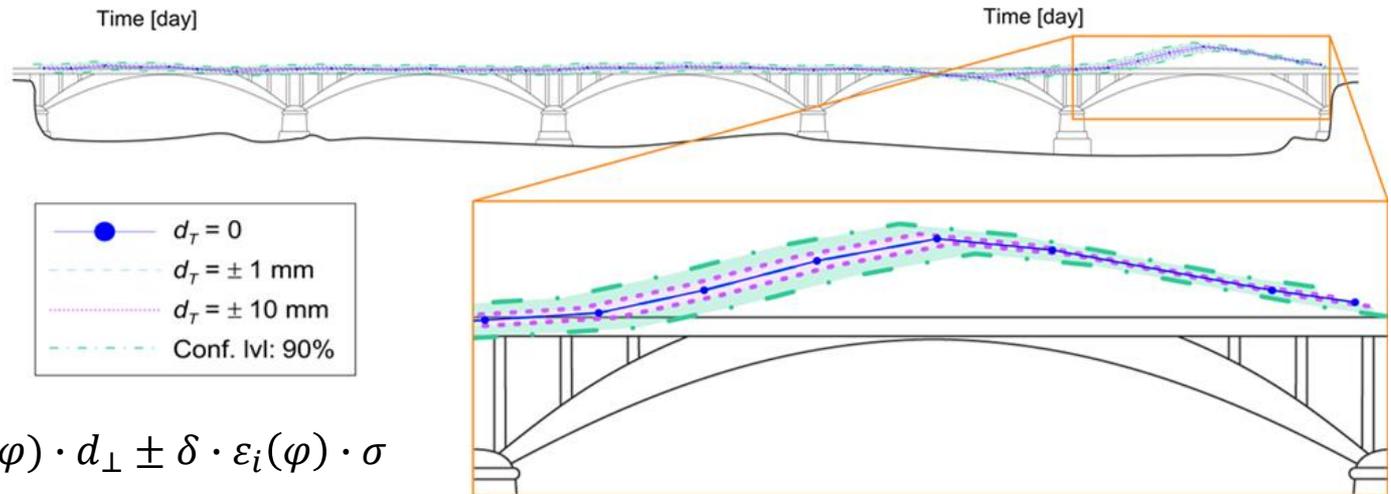
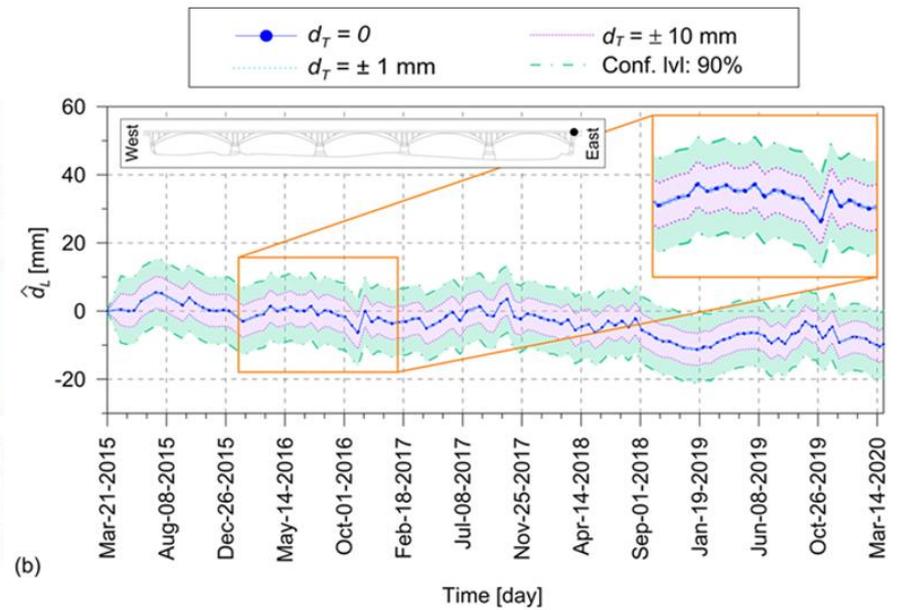
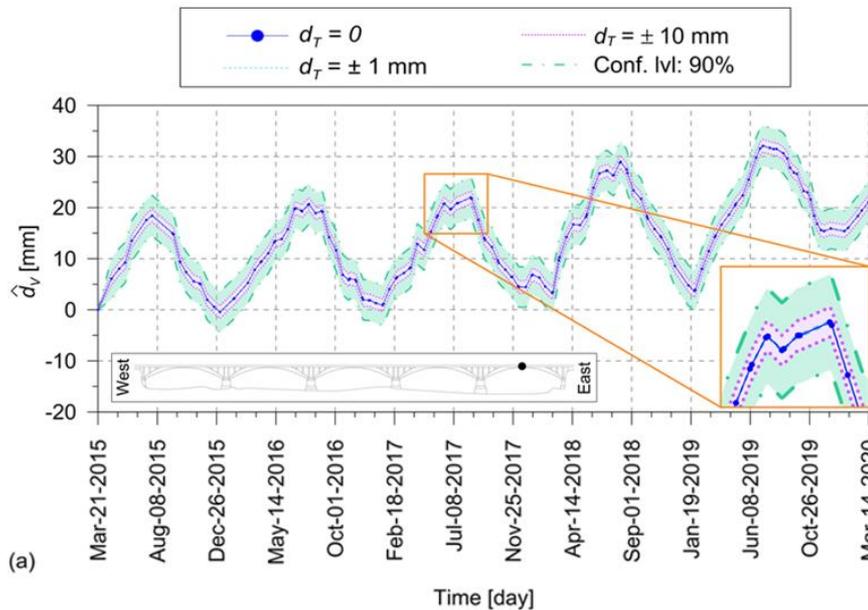


29 Marzo 2020



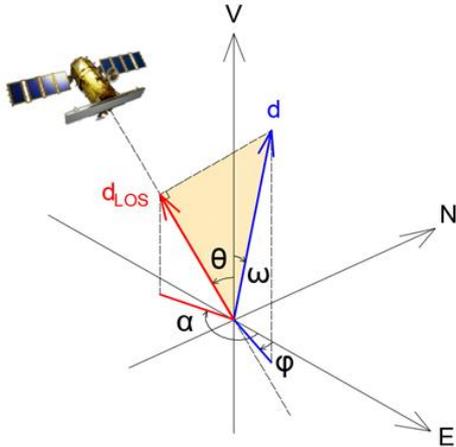
Spostamenti  
rappresentati  
in scala 200:1

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR



$$\hat{d}_i = d_i + c_i(\varphi) \cdot d_{\perp} \pm \delta \cdot \varepsilon_i(\varphi) \cdot \sigma$$

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR

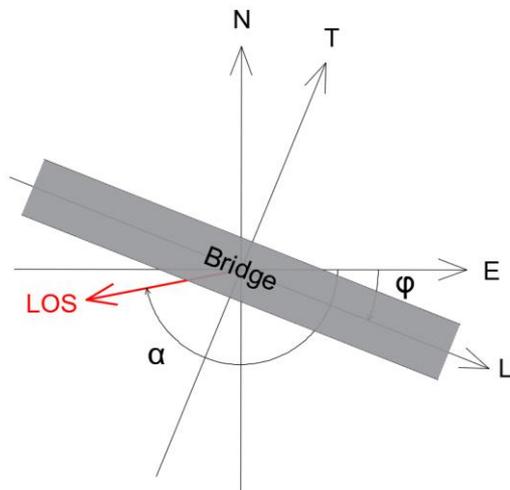


Le tecniche InSAR sono in grado di misurare la proiezione dello spostamento reale 3D lungo la linea di vista (LOS) del sensore

$$d = \frac{d_{LOS}}{\cos \theta \cos \omega + \sin \theta \sin \omega \cos(\alpha - \varphi)}$$

LOS satelliti COSMO-SkyMed:  
 $\theta_A = 32.2^\circ$ ,  $\alpha_A = 168.6^\circ$   
 (geometria ascendente)  
 $\theta_D = 29.4^\circ$ ,  $\alpha_D = 10.3^\circ$   
 (geometria discendente)

Sensibilità delle misure a spostamenti in direzione degli assi del sistema di riferimento locale del ponte ( $L, T, V$ )



$$d_L = \frac{d_{LOS}}{\sin \theta \cos(\alpha - \varphi)} = \frac{d_{LOS}}{s_L}$$

$$d_T = -\frac{d_{LOS}}{\sin \theta \sin(\alpha - \varphi)} = \frac{d_{LOS}}{s_T}$$

$$d_V = \frac{d_{LOS}}{\cos \theta} = \frac{d_{LOS}}{s_V}$$

L'angolo  $\varphi$  definisce l'orientamento del ponte nel piano orizzontale

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR

$$d_{LOS} = d_L \sin \theta \cos(\alpha - \varphi) - d_T \sin \theta \sin(\alpha - \varphi) + d_V \cos \theta$$

Misure InSAR lungo due LOS  
(ascendente e discendente)

$$\mathbf{d}_{LOS} = \mathbf{A} \mathbf{d}$$

$$\mathbf{d}_{LOS} = \begin{Bmatrix} d_{\mathcal{A}} \\ d_{\mathcal{D}} \end{Bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} \sin \theta_{\mathcal{A}} \cos(\alpha_{\mathcal{A}} - \varphi) & -\sin \theta_{\mathcal{A}} \sin(\alpha_{\mathcal{A}} - \varphi) & \cos \theta_{\mathcal{A}} \\ \sin \theta_{\mathcal{D}} \cos(\alpha_{\mathcal{D}} - \varphi) & -\sin \theta_{\mathcal{D}} \sin(\alpha_{\mathcal{D}} - \varphi) & \cos \theta_{\mathcal{D}} \end{bmatrix}$$

$$\mathbf{d} = \begin{Bmatrix} d_L \\ d_T \\ d_V \end{Bmatrix}$$

Ipotesi sulla direzione del  
movimento



Vettore spostamento stimato  
(2 GDL)

$$\hat{\mathbf{d}} = \mathbf{B}^{-1} \mathbf{d}_{LOS}$$

Ipotesi comuni

ASS#1. vettore  $\mathbf{d}$  nel piano  $L-V$

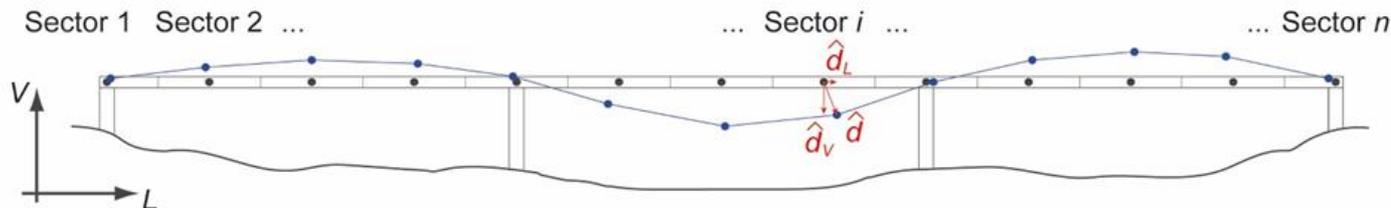
$$\hat{\mathbf{d}} = \begin{Bmatrix} \hat{d}_L \\ \hat{d}_V \end{Bmatrix}, \mathbf{B} = \begin{bmatrix} \sin \theta_{\mathcal{A}} \cos(\alpha_{\mathcal{A}} - \varphi) & \cos \theta_{\mathcal{A}} \\ \sin \theta_{\mathcal{D}} \cos(\alpha_{\mathcal{D}} - \varphi) & \cos \theta_{\mathcal{D}} \end{bmatrix}$$

ASS#2. vettore  $\mathbf{d}$  nel piano  $T-V$

$$\hat{\mathbf{d}} = \begin{Bmatrix} \hat{d}_T \\ \hat{d}_V \end{Bmatrix}, \mathbf{B} = \begin{bmatrix} -\sin \theta_{\mathcal{A}} \sin(\alpha_{\mathcal{A}} - \varphi) & \cos \theta_{\mathcal{A}} \\ -\sin \theta_{\mathcal{D}} \sin(\alpha_{\mathcal{D}} - \varphi) & \cos \theta_{\mathcal{D}} \end{bmatrix}$$

ASS#3. vettore  $\mathbf{d}$  nel piano  $L-T$

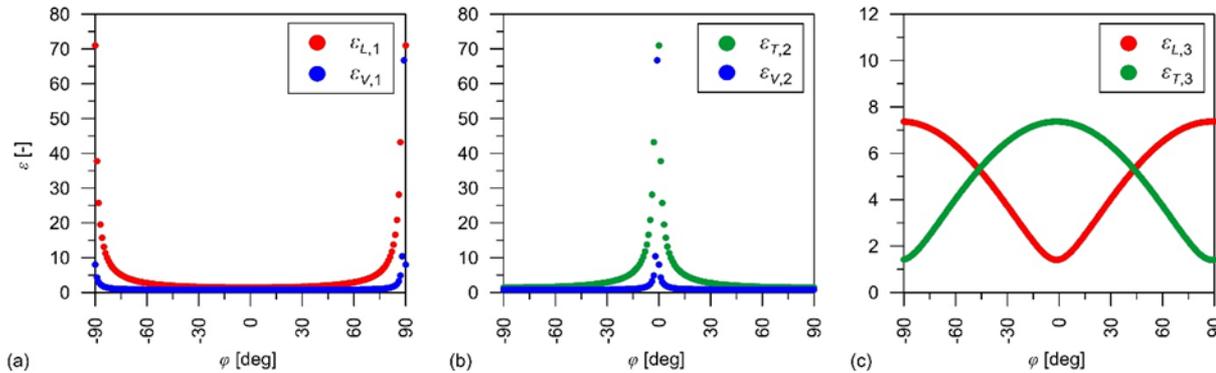
$$\hat{\mathbf{d}} = \begin{Bmatrix} \hat{d}_L \\ \hat{d}_T \end{Bmatrix}, \mathbf{B} = \begin{bmatrix} \sin \theta_{\mathcal{A}} \cos(\alpha_{\mathcal{A}} - \varphi) & -\sin \theta_{\mathcal{A}} \sin(\alpha_{\mathcal{A}} - \varphi) \\ \sin \theta_{\mathcal{D}} \cos(\alpha_{\mathcal{D}} - \varphi) & -\sin \theta_{\mathcal{D}} \sin(\alpha_{\mathcal{D}} - \varphi) \end{bmatrix}$$



Ricostruzione 2D della  
deformata di un ponte  
nel piano  $L-V$  (ASS#1)

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: INSAR

Errori casuali: propagazione dell'errore di misura lungo la LOS



$$\Sigma_{\hat{d}} = \mathbf{B}^{-1} \Sigma_{\text{LOS}} [\mathbf{B}^{-1}]^T$$

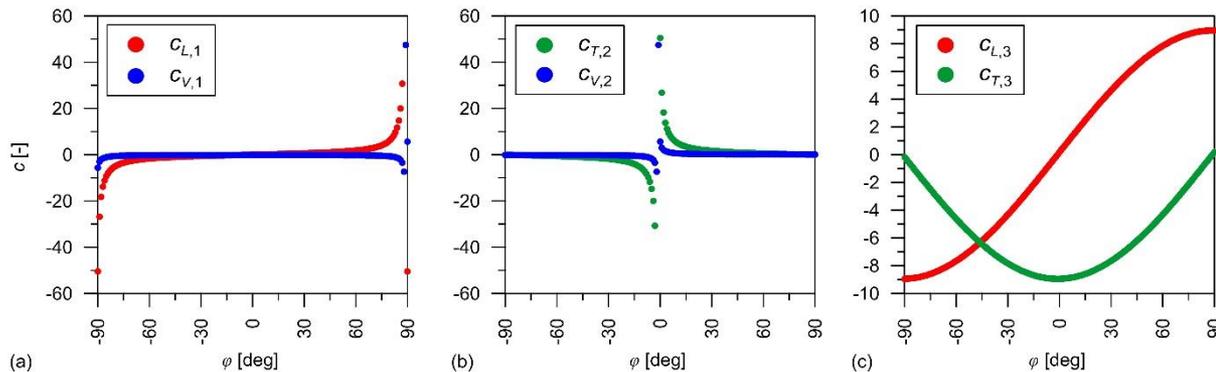
$$\Sigma_{\text{LOS}} = \begin{bmatrix} \sigma_{\mathcal{A}}^2 & \sigma_{\mathcal{AD}} \\ \sigma_{\mathcal{AD}} & \sigma_{\mathcal{D}}^2 \end{bmatrix}$$

$$\sigma_{\hat{d}_i}^2 = a_i^2 \sigma_{\mathcal{A}}^2 + b_i^2 \sigma_{\mathcal{D}}^2, \quad \sigma_{\mathcal{A}}^2 = \sigma_{\mathcal{D}}^2 = \sigma^2$$

$$\sigma_{\hat{d}_i} = \sqrt{a_i^2(\varphi) + b_i^2(\varphi)} \cdot \sigma = \varepsilon_i(\varphi) \cdot \sigma$$

$\varepsilon_i(\varphi)$ : coefficienti di diluizione

Errori sistematici: ipotesi di base non corretta



$$\hat{\mathbf{d}} = \mathbf{B}^{-1} \mathbf{A} \mathbf{d} = \mathbf{C} \mathbf{d}$$

$$\text{ASS\#1. } \mathbf{C} = \begin{bmatrix} 1 & c_{L,1} & 0 \\ 0 & c_{V,1} & 1 \end{bmatrix}$$

$$\text{ASS\#2. } \mathbf{C} = \begin{bmatrix} c_{T,2} & 1 & 0 \\ c_{V,2} & 0 & 1 \end{bmatrix}$$

$$\text{ASS\#3. } \mathbf{C} = \begin{bmatrix} 1 & 0 & c_{L,3} \\ 0 & 1 & c_{T,3} \end{bmatrix}$$

$$\hat{d}_i = d_i + c_i(\varphi) \cdot d_{\perp}$$

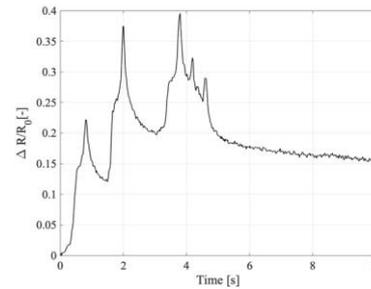
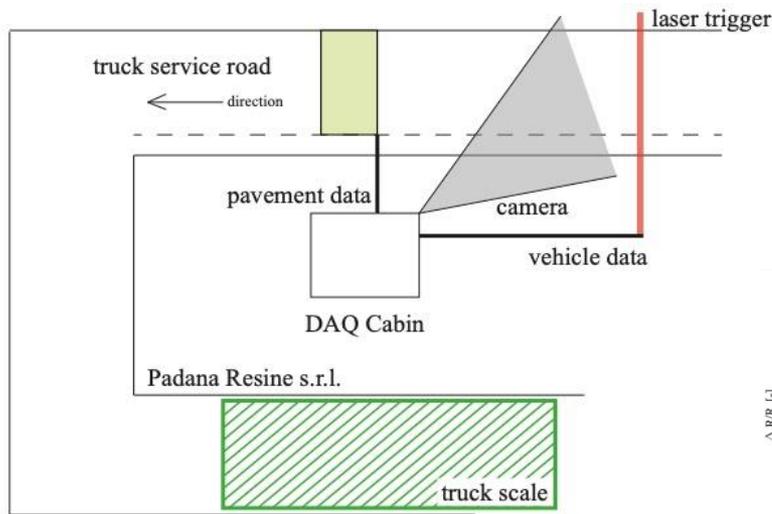
$c_i(\varphi)$ : coefficienti di ponderazione

Errori totali:  $\hat{d}_i = d_i + c_i(\varphi) \cdot d_{\perp} \pm \delta \cdot \varepsilon_i(\varphi) \cdot \sigma$

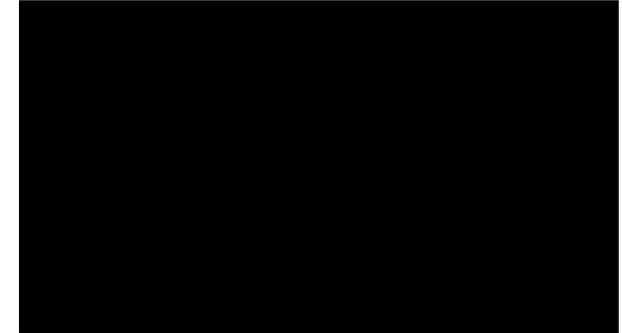
$\delta$ : coefficiente di confidenza

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: WIM

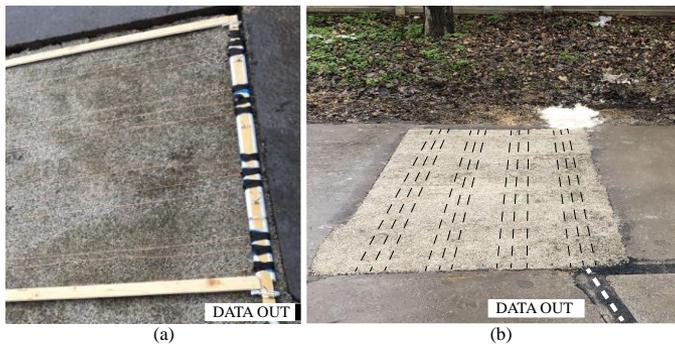
Field setup and typical outcome:



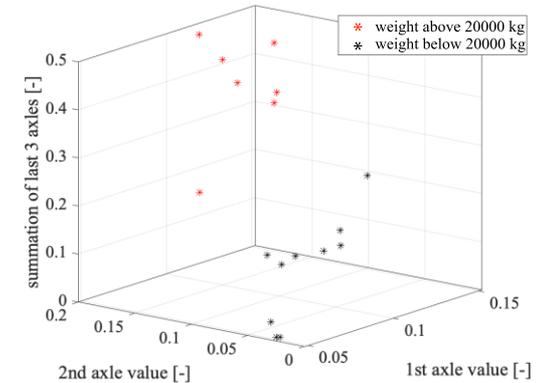
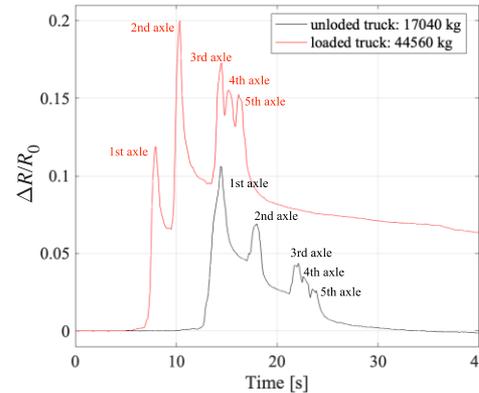
Operation video:



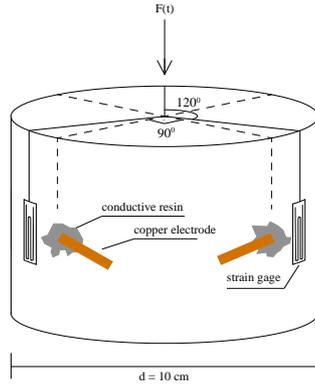
EVlzero smart pavement electrodes design:



Truck signal examples and weight categorization



# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: WIM



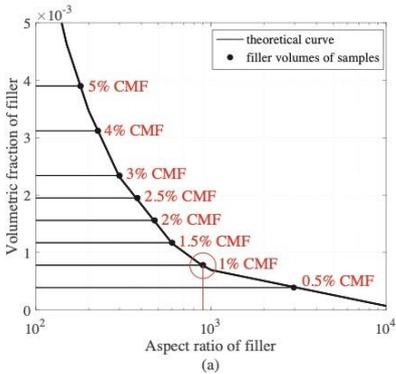
optimal

\*CMF-% with respect to EVIzero weight

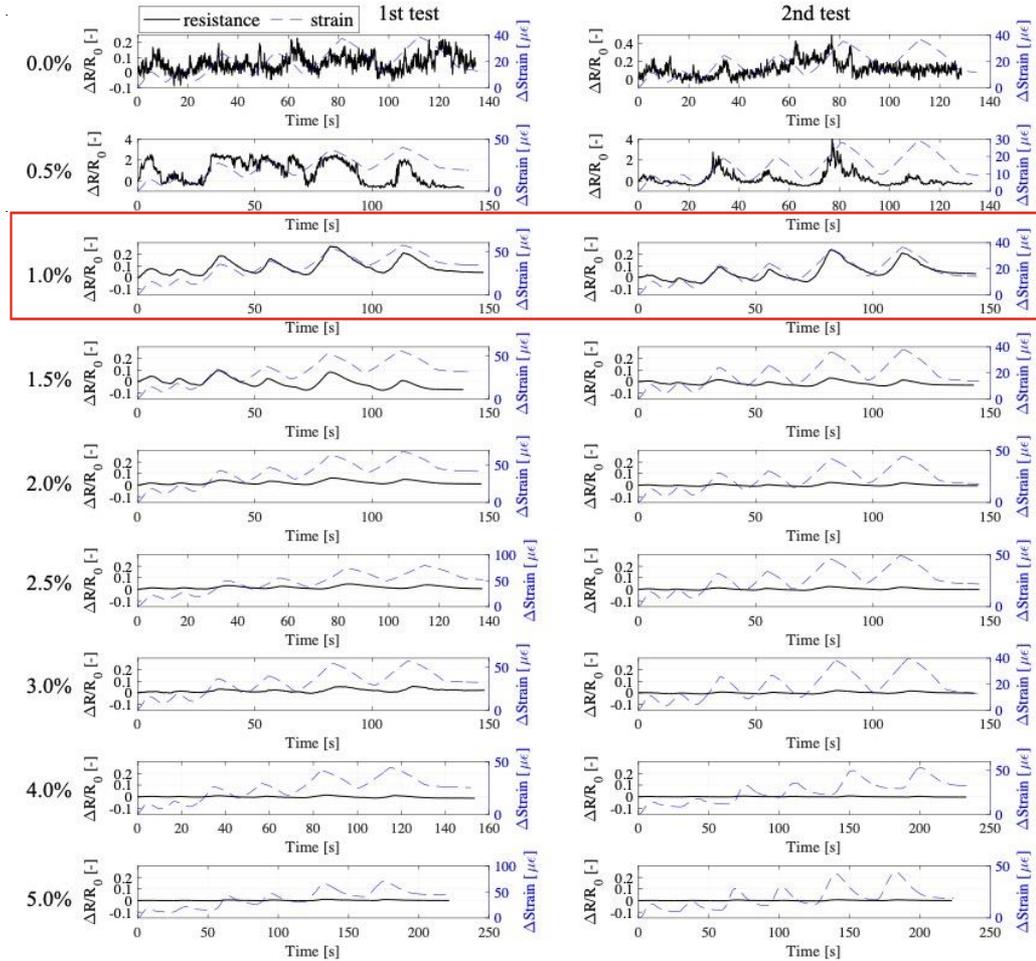
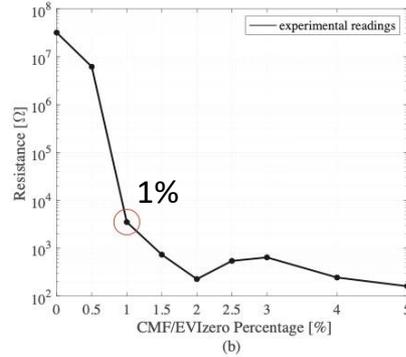
CMF aspect ratio ~1000

EVIzero is non-conductor, material matrix is assumed to have void conditions for electrical conductivity.

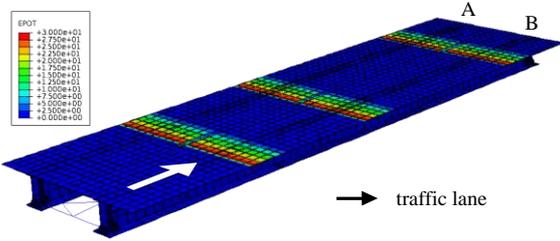
Analytical percolation:



Experimental percolation:



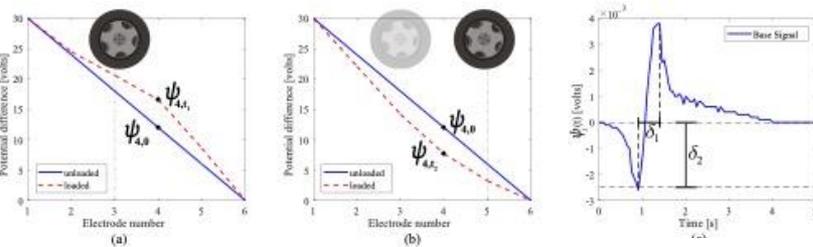
# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: WIM



## FEM algorithm results:

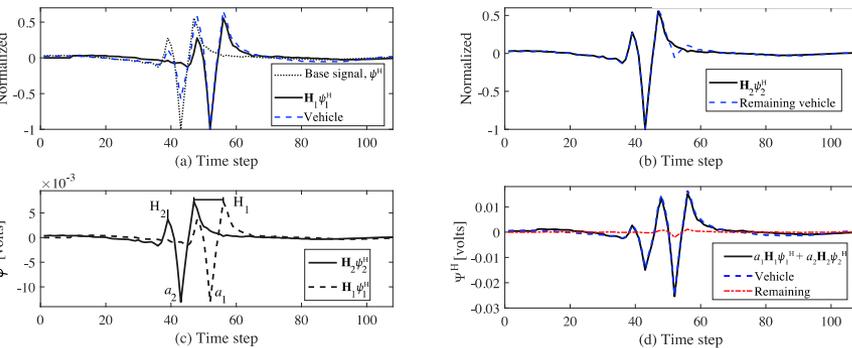
	Input		Weigh - in - motion			
	Eurocode		Case I		Case II	
	Axle Spacing (m)	Axle Weights (kN)	Axle Spacing (m)	Axle Weights (kN)	Axle Spacing (m)	Axle Weights (kN)
Type I	4,5	90 190	4,5	90 196	4,5	81 177
Type II	4,2 1,3	80 140 140	4 1,5	77 125 155	4,5 1	93 162 115
Type III	3,2 5,2 1,3 1,3	90 180 120 120	3 5,5 2 1,5	91 171 148 158		46

## FEM generated base signals to represent axle pass:



## Superposition to imitate vehicle geometry:

$$\Psi(t) = \sum_{j=1}^n \psi_j(t)$$

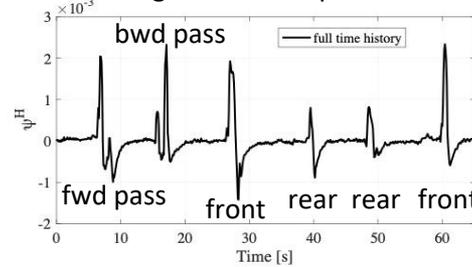


## Cost function to determine axle weights and separations:

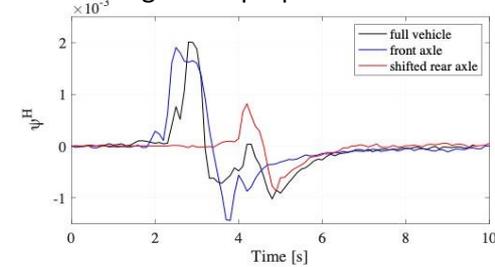
$$E = \|\Psi^H(t) - \sum_{j=1}^n a_j \mathbf{H}_j \psi_j^H(t)\|^2$$

## Field trial with car:

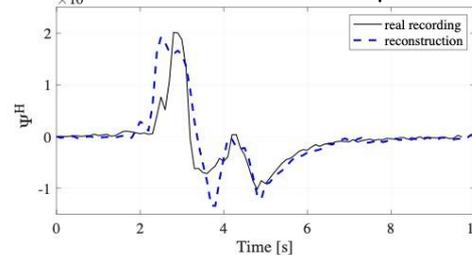
### recordings with smart pavement:



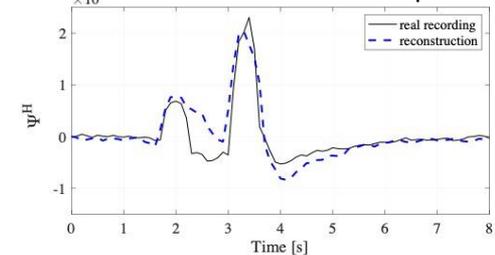
### shifting and superposition:



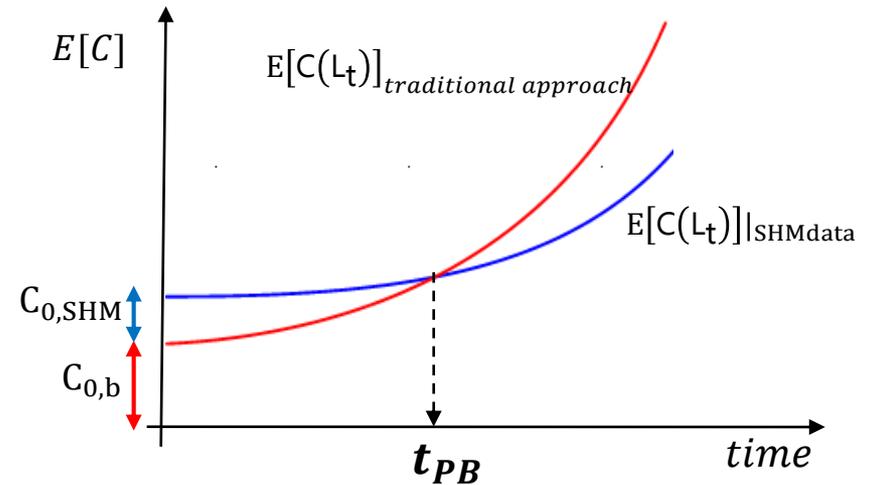
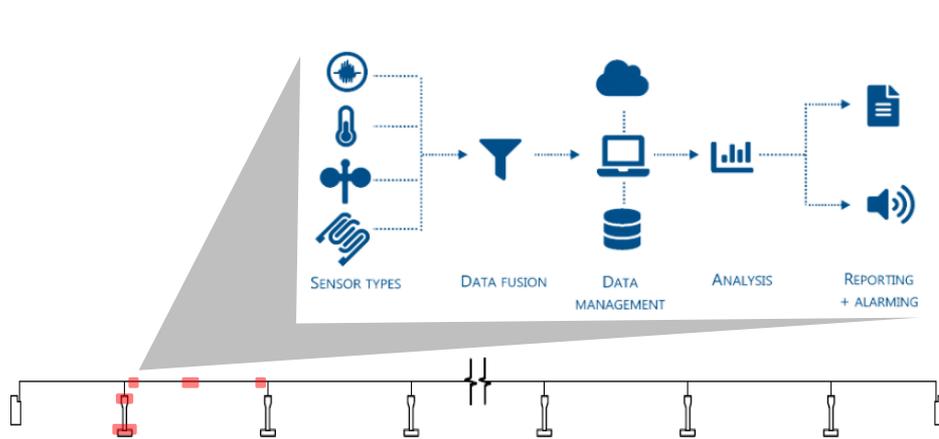
### reconstructed forward pass:



### reconstructed backward pass:



# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: WIM



EXPECTED TOTAL  
LCC

INITIAL COSTS

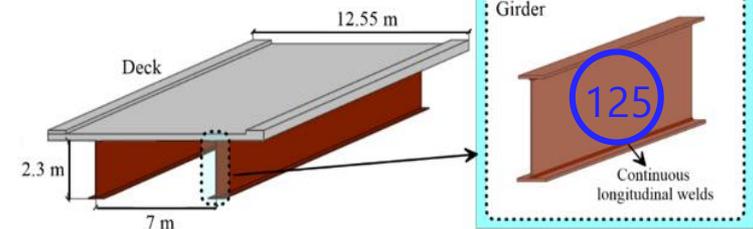
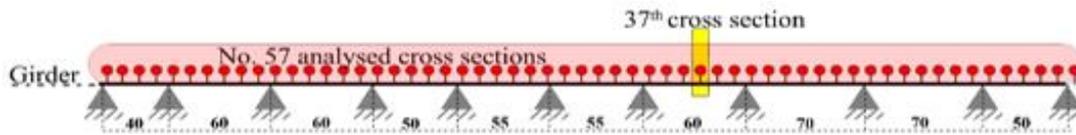
MANAGEMENT COSTS

$$E[C(t_L)] = C_{0,b} + C_{0,SHM} + \sum_{t=1}^{t_L} \left[ \frac{E[C_S(t)] + E[C_I(t)] + E[C_R(t)]}{(1+r)^t} \right]$$

$$E[\cdot] = p_f(\mathbf{SHM\ data}) \cdot c_u$$

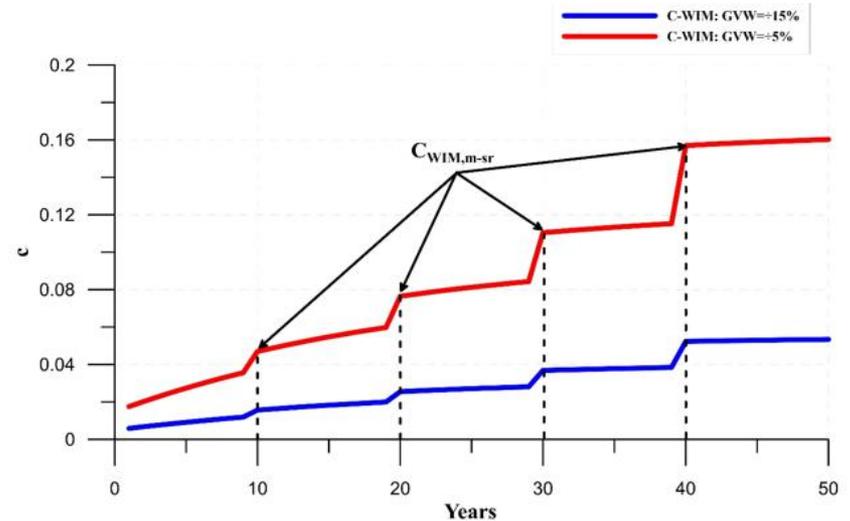
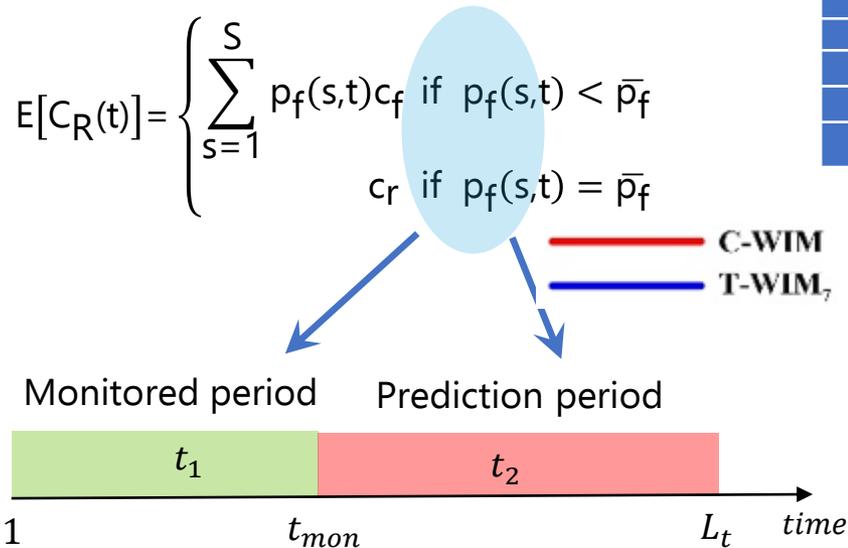
$$P_f = \int \int P(\mathbf{DS}|\mathbf{EDP})f(\mathbf{EDP}|\mathbf{IM})d(\mathbf{EDP})f(\mathbf{IM})(t)d(\mathbf{IM})$$

# SENSORISTICA DI MONITORAGGIO NON CONVENZIONALE: WIM



$$E[C(L_t)]|_{WIMdata} = C_I + C_{WIM,I} + \sum_{t_1=1}^{t_{mon}} \frac{C_{WIM,M}(t_1)}{(1+r)^{t_1}} + \sum_{t=1}^{L_t} \frac{E[C_R(t)]|_{WIMdata}}{(1+r)^t}$$

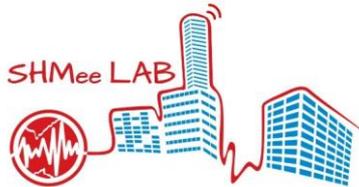
Cost item	Cost (€)   GVW= ±15%	Cost (€)   GVW= ±5%
$c_r$	200.000	200.000
$c_f$	2.000.000	2.000.000
$C_{WIM,I}$	20.000	60.000
$C_{WIM,m-s}$	4.000/year	12.000/year
$C_{WIM,m-sr}$	8.000/10 years	24.000/10 years



## CONCLUSIONI

- Nel monitoraggio dinamico e misto statico-dinamico dei ponti appaiono particolarmente promettenti alcune tecniche non convenzionali di analisi dei segnali: metodi di AI (es LAR, clustering non parametrico, autoencoders, LSTM, ecc) e interferometri sismica
- Le tecniche INSAR possono fornire informazioni molto utili sul comportamento dei ponti, in particolare con riferimento alle loro interazioni con frane. Occorre però quantificare attentamente errori sistematici e casuali come proposto recentemente dal gruppo di ricerca.
- I sistemi WIM possono produrre un notevole risparmio in termini di costo di ciclo di vita di un ponte. Particolarmente promettenti appare lo sviluppo di pavimentazioni intelligenti a basso costo.

# GRAZIE PER L'ATTENZIONE!



Thank you

[filippo.ubertini@unipg.it](mailto:filippo.ubertini@unipg.it)

[www.shmlab.weebly.com](http://www.shmlab.weebly.com)



*This project has received funding from the European Union's Framework Programme for Research and Innovation HORIZON 2020 under grant agreement No 700395*



**SMARTERICK**



**SAFERUP!**  
Thinking Beyond the Pavement



*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 765057*



FONDAZIONE  
CASSA RISPARMIO PERUGIA